The Stellar Populations of Spiral Disks. I. A New Observational Approach: Description of the Technique and Spectral Gradients for the Inter–Arm Regions of NGC 4321 (M 100)

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ABSTRACT

We describe an imaging method that makes use of interference filters to provide integrated stellar spectral indices for spiral disks to faint surface brightness limits. We use filters with bandpasses ~ 60Å FWHM, centered on the Mg and Fe features ($\lambda\lambda 5176$ Å and 5270 Å respectively) allowing the determination of the spatial distribution of the Lick indices Mg_2 and Fe5270. These two indices have been extensively modeled by different groups and used in the past mainly for the study of elliptical galaxies, bulges, and globular clusters. Azimuthal integration of the underlying smooth stellar signal, after removal of the signature of the spiral arms and associated extreme pop. I structures, provides measurements of these spectral indices useful to radial distances where the surface brightness of the galaxy reaches $\sim 24\mu_V$.

As a first example of this technique and its possibilities we conduct a preliminary study of the SABbc galaxy NGC 4321 (M 100). We present spectral gradients for the inter–arm stellar population to about 4 exponential scale lengths. There is some evidence for a discontinuity in the run of the Mg_2 index near corotation, which we interpret as evidence for bar– driven secular evolution. There is also evidence that Mg is overabundant with respect to Fe in the inner regions of the projected image.

1.   Introduction

Spectral gradients contain a wealth of information on the stellar populations of galaxies, and therefore on their formation and evolution. Studies of gradients in ellipticals and S0 galaxies, where the surface brightness remain high to large radii, are by now common (Couture & Hardy 1988, Gorgas et al. 1990, Davidge 1992, Carollo et al. 1993, Davies et al. 1993 Casuso et al. 1996). For spiral galaxies, especially late-type ones, chemical gradients have been under study for a long time using the information provided by the bright emission lines of their H II regions, for which the physics is well understood. H II regions have indeed provided α-element abundances for the gas-phase of spirals to large radial distances (Belley & Roy 1992, Scowen et al. 1992, Martin & Roy 1994, Zaritsky et al. 1994). A number of recent investigations on the integrated spectra of spiral *bulges* provide information on their age and metallicity structure, much as has been done with ellipticals (Jablonka et al. 1996; Idiart et al. 1996, Davidge 1997). Little is known however about the spectral properties of the *stellar* disks of external spirals (but see Monteverde et al., 1997 for a study of abundances of O stars in M33, and Brewer, Richer & Crabtree, 1995 for an indirect estimate of the stellar metallicity gradient in M31 from C to M stars ratios).

The integrated light of the inter–arm regions of spiral disks contains a light-weighted chemical signature complementary to that of H II regions. We observe in stellar disks a time average over their chemical history, as opposed to the accummulated effect on the extreme population I component revealed by the properties of the excited gas. In addition, the chemistry of stellar disks may contain valuable information on the dynamical instabilities and secular evolution introduced by common non-axisymmetric perturbations such as oval structures and bars (Friedli & Benz 1995, Courteau et al. 1996). Furthermore, and this is an issue we will explore briefly in this paper, it is possible to separate in the integrated light of stellar disks the contribution of the α-elements from that of the Fe-group elements,

something that has not yet been possible for H II regions. Indeed, stellar iron features, such as Fe5270 and Fe5335, are commonly used as indicators for species formed in the low-mass stellar progenitors of SNeI, although some Fe is also formed in SNeII. Magnesium features such as the one centered at λ 5176 Å, are indicators of α-elements formed in the SNeII explosions in which high-mass stars end their life (see Worthey et al. 1992). One must keep in mind however that all integrated stellar spectral indices used to derive abundances contain also an age dependence that must be taken into account.

Observing the spectral signature of a stellar disk with reasonable S/N ratios is a difficult task as its surface brightness, which decreases exponentially with radial distance from the center, reaches very low levels quickly. Indeed, for most late-type spirals, with exponential length scales smaller than 5 kpc, the surface brightness at 10 kpc is fainter than $24\mu_B$, well below that of the night sky. The long-slit spectroscopic technique employed in the study of ellipticals becomes unsuitable for spirals even for 4m-class telescopes, especially at low light levels where accurate sky-subtraction is critical. The use of modern large-format imaging CCD detectors combined with large fields of view and well-tested imaging analysis techniques provides a useful alternative, as shown in this investigation.

In this paper, the first of a series, we describe an imaging method that uses relatively narrow (~ 60 Å) filters designed to isolate the Mg and Fe spectral features indicated above. This technique which allows azimuthal integration of the signal over the surface of the disk has not been used previously on spirals, and we will show that it is capable of providing good S/N ratios to large radial distances. We concentrate here heavily on technical issues leaving most aspects of the calibration of the spectral indices in terms of actual abundances for later publications. Results for the SABbc galaxy NGC 4321 (M 100), a galaxy which has been extensively studied, and which we used as our test–bench, will however be presented.

The following simple order–of–magnitude computation shows the dramatic increase in

S/N afforded by the present method when compared to the conventional method of long–slit spectroscopy, especially at large radial distances. We are here setting aside the obvious multiplexing advantage of a spectrograph. Consider the case of M 100, and a section at R_{25} = 222″. Let us assume that we are using a grating that provides (as in §3) a resolution of 34 Å FWHM, compatible with the indices studied here, and corresponding to a slit width of 6″.1 . Let us further assume that we integrate the spectrum along the slit within a radial interval of 16″ providing a resolution element of ~ 100 □″ . The surface of an annulus of the same radial width and inner radius is $\sim 2.3 \times 10^4$ □″. In other words, if we concentrate on one spectral feature, azimuthal integration of the annulus using images taken through a narrow band-pass filter provides the equivalent of a signal about 230 times larger than that obtained from a slit observation, for the same spectral and radial resolution. For a low readout noise CCD, this translates into an increase in the effective S/N of the measurement $per filter$ approaching a factor 15. The total readout noise will however increase as a result of the increased number of summed pixels, but the precision of the sky sampling will be higher, as will be the effective quantum efficiency of a CCD + filter combination which is at least 2–3 times that of a grating spectrograph. Furthermore, as discussed in §2, three filters are needed per spectral index (one for the feature and two for the continua), thus increasing the total exposure time in the imaging method. When all of this is taken into consideration the expected improvement in S/N for equal pixel binning and exposure time is still close to a very substantial factor 10. The relative improvement is, of course, larger at large radial distances where the S/N ratio per unit surface is lowest. For edge–on spirals our argument is certainly less compelling, as they would exhibit a higher projected surface brightness along the slit. Yet, increased internal absorption and the inhability to isolate the underlying smooth stellar disk from the arm component are important limitations associated with the study of edge–on spirals.

The use of an interference filter–CCD combination to isolate spectral features in the

integrated stellar light of galaxies is not new. For example, Thomsen & Baum (1989 and references therein), have used it to examine the Mg behavior within ellipticals in the Coma cluster of galaxies. We use such a technique here on spiral disks for the first time and pool together the imaging data obtained through different bandpasses, including wideband ones, to separate the information belonging to the inter–arm regions of nearly face–on galaxies from that of the spiral arms.

The interference filter set described below was designed for a mean target velocity close to that of the Virgo cluster. At that distance we have excellent spatial resolution per flux unit, atmospheric seeing does not become an important problem, and our bandpasses do not become contaminated by any strong sky emission line. We have chosen here nearly face-on galaxies for the reasons already discused and to increase the number of available pixels (see §4.1.3), and minimize rotational effects, but it will certainly be very rewarding in the future to observe edge-on galaxies with the same technique in order to explore the disk-halo connection. Our use of a focal reducer with a large field of view rendered the determination of the sky level of our images feasible even at the relatively short distances of our sample.

In subsequent publications we will combine this observational technique, as applied to a larger sample of galaxies, with the results of spectral synthesis, of models of chemical evolution of spiral galaxies, and of numerical simulations. When combined with observations of chemical gradients derived from H II regions, these results will be valuable in improving our understanding of spiral galaxies.

This paper is organized as follows. In §2 we discuss the method and in particular the filter system adopted; we describe the observations in §3, the reduction techniques and calibrations in §4, and in §5 we present the first results for M 100 (NGC 4321).

2. The Method

We have chosen to work on two spectral features: the Mg_2 molecular feature, and the Fe5270 absorption line (Faber et al. 1985, and references therein (hereafter FFBG85), Burstein et al. 1984; Worthey et al. 1992). These two indices have been extensively modeled by different groups (Worthey 1994; Chavez et al. 1995; Chavez et al. 1996, Idiart et al 1996) and should prove useful in describing the radial behavior of chemical abundances for the two groups of elements mentioned in §1. They are defined within a restricted spectral interval, and their sensitivity to dust absorption should be small (see §4.2.4). Table 1 provides the spectral information on the 4 filters used, which were built for us by Andover Co., and which were designed for objects centered at a velocity of 2000 km s^{-1} (at 23 °C). The top panel of Figure 1 displays the spectrum of a K giant, whereas the bottom panel shows the location and transmittance curves of the filters. Notice the important caveat that although we have fully respected the Lick definition for Mg_2 (Burstein et al. 1984), we have not done so for the Fe5270 feature. In the latter case we have decided to adopt provisionally a pseudo–Fe5270 index that retains the original Lick Fe absorption bandpass, but uses the same continua bandpasses as the Mg_2 feature to define the pseudo–index Fe5270′. We did so in order to reduce the total number of filters required and save observing time while testing to at least a first approximation the Fe behavior. As it turned out this inconsistency is not a fundamental limitation because the pseudo–index can be well calibrated in terms of the true Lick index, as we will show in §4.

Because the effective wavelengths of interference filters shift towards the blue with increasing inclination (~ 1 Å per degree, up to 5°) and decreasing temperature (~ 0.2 Å per °C), they must be fine–tuned at the telescope. Given the widths of the filters (about 60 Å FWHM), the average nightly temperature, and the tilting capabilities at our disposal, we could observe galaxies spanning the approximate velocity interval 1400 km s^{-1}

– 2100 km s^{-1}. This interval was quite appropriate for Virgo spirals. Notice that the strong [OII] $\lambda5577$Å atmospheric emission line falls to the red of our filters, an important consideration when dealing with photometry at small surface brightness levels (see Baum et al. 1986).

3. Observations

All observations presented here were conducted at the 1.6 m telescope of the Observatoire du mont Mégantic (OMM). We used the f/2 focal reducer PANORAMIX built by Dr. J.–R. Roy for imaging, outfitted with a special filterholder that allows for variable filter inclinations. Spectroscopy was conducted with the standard OMM Boller & Chivens long–slit spectrograph. The same 1024×1024 Thomson CCD detector with a pixel size of 19 μm was employed for both types of observations. The setups are summarized on Tables 2 and 3. The relevant properties of M 100, including its distance and scale, are summarized on Table 4 following the usual notation.

Images obtained through interference filters provide uncalibrated indices, which must then be brought into the Lick standard system. This correction is obtained in two steps via spectroscopic observations. First, spectroscopy of a number of bright Lick standard stars and some galaxies having published indices were used to set the calibration slopes that transform our filter system into the Lick system via numerical integration of the observed energy distribution within each filter bandpass. Since our filter definition for the Mg$_2$ feature closely matches the standard definition we expected from the onset to obtain a slope close to unit, as was indeed the case, but this would certainly not be true of the Fe5270 index. The second step involves the computation of the zero point of the system for each galaxy. Since the indices are formed by combining sequences of images taken through different filters under variable atmospheric conditions, their zero points must be established

from spectroscopy of the bright nuclear regions of the target galaxies so as to observe the entire spectral range required simultaneously. These and other aspects of the calibration will be discussed in detail in the following section.

A complete set of biases, dome flats and sky flats was obtained on each night reaching count levels approximately equal to half the full–well capacity of the CCD. Dark count rates proved variable, and a set of small masks near the periphery of the field were used to measure for every exposure the additive signal composed of the dark signal plus the diffuse-light component.

4. Data Reduction

We reduced all the data, images and long–slit spectra, using IRAF[1] tasks to subtract the overscan, the bias, and the dark plus diffuse-light frame, and to divide by the flatfield. Cosmic rays were rejected by the usual clipping algorithm applied to multiple images.

Following the correction of all frames for the instrumental signature we co–added the information after performing the geometrical registration needed to place all images on the same coordinate system.

4.1. Obtaining Instrumental Spectral Indices from Images

All indices were derived from the instrumental integrated fluxes derived from azimuthal integration within annuli. We retained however the identity of each pixel within a given

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annulus in order to be able to tag it for inclusion or exclusion via a mask function $\aleph(r, \theta)$ (= 1 for valid pixels, 0 otherwise). This mask was used to characterize each pixel as belonging to the disk in the inter–arm region, or to the spiral arms, and reject foreground and background contamination; we stress here that the imaging method on near face–on galaxies allows a direct way of computing $\aleph(r, \theta)$.

The following equations were adopted to compute the indices:

$$\mathrm{Mg_2} = -2.5 \log \left(\frac{\mathcal{F}_{\mathrm{Mg_2}}}{\mathcal{F}_{\mathrm{C}}} \right) \quad [\mathrm{mag}] \tag{1}$$

$$\mathrm{Fe5270}' = \Delta\lambda \left(1 - \frac{\mathcal{F}_{\mathrm{Fe5270}}}{\mathcal{F}_{\mathrm{Cw}}} \right) \quad [\mathrm{\AA}] \tag{2}$$

where the $\mathcal{F}$'s stand for the total sky-subtracted flux seen through each filter within a given annulus, as given by the following expression:

$$\mathcal{F} = \sum_{i=1}^{n} \mathrm{pixel}_n = \int_0^{2\pi} \int_{r_0}^{r_0 + \Delta r} f(r, \theta) \aleph(r, \theta) dr d\theta \quad [\mathrm{e}^-] \tag{3}$$

In the preceding equations n is the number of pixels inside an annulus, r_0 is the inner radius of this annulus, Δr is its width, $f(r, \theta)$ is the flux at a given pixel. The subscript C indicates the continuum level associated to a given bandpass. Equation 3 can thus be understood as the sum of the sky-subtracted counts in all valid pixels inside an annulus for a given filter. In the equation for Fe5270', $\Delta\lambda$ is the FWHM of the central filter (e.g. 55 Å ; see Table 1).

The arithmetic mean of the continua (indicated by the subscript C) is used to compute the $\mathrm{Mg_2}$ index. But since the Fe5270' feature is much closer to the adopted red continuum than to the blue one, a weighted geometrical mean of the continuum at the feature position (indicated by $\mathrm{C_w}$) was adopted for the computation of Fe5270' index. The adopted continuum values are given by:

$$\mathcal{F}_{\mathrm{C}} = \frac{\mathcal{F}_{\mathrm{BC}} + \mathcal{F}_{\mathrm{RC}}}{2} \tag{4}$$

$$\mathcal{F}_{\mathrm{Cw}} = \mathcal{F}_{\mathrm{BC}}^a \cdot \mathcal{F}_{\mathrm{RC}}^b \tag{5}$$

where $a = 0.184$ and $b = 0.816$. These values represent the ratio of the distance in λ between the Fe bandpass and each continuum bandpasses. Notice that Equation 5 (where $a + b = 1$) is a good approximation of Equation 4 for symmetric continuum bandpasses (i.e. $a = b$)

The details of the calculations of the errors associated with the spectral indices are given in Appendix A. These calculations provide a reasonable approximation to the errors. Some small factors are nevertheless neglected such as the intrinsic dispersion due to the spectral gradient within a bin.

4.1.1. Image Tabulation

In order to perform the azimuthal integration, the images were tabulated to produce files containing as entries the flux for each pixel on each band, and its position (in cartesian coordinates relative to a corner of the image). Because we wanted to mask foreground stars and other unwanted objects such as residual cosmic rays and background galaxies, we produced a mask image which was included in the main table. It was thus easy to reject all entries corresponding to these masked pixels.

Once the tabulation was done the coordinates relative to the centroid of the galaxy were computed:

$$x' = x - x_C \quad [\text{pixels}] \tag{6}$$

$$y' = y - y_C \quad [\text{pixels}] \tag{7}$$

where (x, y) are measured relative to the image, (x', y') to the centroid, and (x_C, y_C) are the position of the centroid relative to the image. This corresponds to a simple translation. The coordinate system is then deprojected to produce a face–on view. Deprojection (which

involves about 1 million pixels) is done by a simple matrix:

$$
\begin{bmatrix} x_\circ \\ y_\circ \end{bmatrix} = s \begin{bmatrix} \cos P.A./\cos i & \sin P.A./\cos i \\ -\sin P.A. & \cos P.A. \end{bmatrix} \begin{bmatrix} x' \\ y' \end{bmatrix} \quad ['']
\tag{8}
$$

where $x_\circ$ and $y_\circ$ are coordinates after deprojection, $P.A.$ is the position angle, i is the inclination and s is the image scale in $''$/pixel. For each pixel, the *deprojected* distance to the centroid was then computed:

$$
r_\circ = \sqrt{x_\circ^2 + y_\circ^2} \quad ['']
\tag{9}
$$

The following entries were tabulated after completion of the above operations: $\mathcal{F}_{BC}$, $\mathcal{F}_{Mg_2}$, $\mathcal{F}_{Fe5270'}$, $\mathcal{F}_{RC}$, $\mathcal{F}_C$, $\mathcal{F}_{C_w}$ x, y, x', y', $x_\circ$, $y_\circ$ and $r_\circ$. To these we added $\mathcal{F}_{V'}$ and $\mathcal{F}_I$ (see §4.1.3).

The master table was then segmented into annular bins $10''$ wide, a good compromise between good radial resolution (requiring small bins) and good S/N (requiring large ones). For each annulus and each band the mean, median and standard deviation were then computed for the *mean* radial distance r of the bin, which from then on will characterize it. This produced a new table containing, for each bin: $\overline{\mathcal{F}_\alpha}$, $\sigma_{\mathcal{F}_\alpha}$, $\mathrm{med}(\mathcal{F}_\alpha)$, where α stands for C, C_w, Mg_2, Fe5270$'$ and $r_\circ$, and n the number of pixels per bin. We then computed the ratios of annuli's mean radius to the galaxy's *effective radius* (R_{eff}) and *isophotal radius* (R_{25}) so as to be able to plot all galaxies on the same scale.

4.1.2. Sky Level Computation

In order to compute indices the sky level has to be subtracted accurately from all pixel values as indicated in Equations 1 and 2. The sky level is an *additive* constant and it will obviously introduce non-linear effects on the computed indices if it is not correctly removed.

Errors in this quantity will be less important close to the nucleus where the flux from the object dominates, but they will grow in importance as the object dims with increasing radius. At the outer limits where the surface brightness is very low the sky subtraction is extremely critical, and at R_{25}, the ratio sky/galaxy reaches 100.

We tested a number of methods to compute the mode of the distribution of sky pixels. We fitted gaussians to the histogram and also computed the mean and the median on the most distant annuli ($450'' \leq R \leq 520''$). The mean-median difference is an estimator of the skewness of distribution (i.e, Wadsworth, 1990, pp. 2.8) resulting from a galaxy halo, bad (cold and hot) pixels and cosmic rays that have been missed by the rejection algorithm (as is often the case with grazing rays). We concluded that the best way to proceed was to compute the median of all pixels located further away than a number x of isophotal radii (R_{25}, from RC3, de Vaucouleurs et al. 1991). At this distance from the centroid, the distribution in intensity is close enough to a gaussian so we do not have to care about any skewness. The number of points is large enough to provide a good estimate of the mode with the median. In order to find the best radius x for the sky level computation, we plotted the luminosity profile and chose a range where we could not detect any statistically significant deviation from a constant. Since spiral galaxies fall exponentially, 1 isophotal radius turned out to be a fairly good choice for the beginning of such range.

It is obvious that flat fielding–which we obtained from twilight exposures–is critical and much care must be exercized in making sure that no large–scale components remain. Fortunately, small–scale variations are smoothed out by the azimuthal integration. When the sky level is computed from pixels located at all position angles within a chosen background region, the same smoothing is *de facto* applied.

4.1.3. Arm Rejection

One of the aims of this investigation was to isolate the different populations superimposed on the disks of spirals. This means that we had to mask the extreme population I component made out of gas and young stars belonging to the arms. The integrated signal from these stars is bluer (and brighter) than the inter–arm population and can be removed from the pixel list via color *and* brightness criteria. To this purpose a color image was computed from V' and I images. Here V' is a synthesized V band made from the sum of all four filter bandpasses, which has an effective wavelength close to that of the standard V system. The flux criterion by which only blue pixels *brighter* than a pre-assigned value was used to prevent low S/N pixels from being rejected. Such faint pixels could have a blue color entirely due to noise-induced fluctuations and would tend to introduce a bias toward the red. Knapen & Beckman (1996) used an Hα image in order to outline star formation regions (see their Figure 5). We believe our method to be as good as theirs because it operates at the smaller pixel scale. Nevertheless, the criticallity of the rejection criteria is somewhat alleviated by the conclusion that the arms covered a rather small surface compared to the disk. Beckman et al. (1996) propose a restricted version of the present method by rejecting pixels having a flux 7% higher than the mean I band value at a given radius. This rejection process, based only on a flux criterion, is probably not as good in general as the one based on Hα image because it can lead to systematic under–rejection in annuli intercepted by quasi-circular arms.

4.2. Calibrating the Indices into the Lick System

So far we have built a 2-D collection of spectral indices in an instrumental system which would depend on a number of factors. These are the filters' design, small velocity-dependent differences between the bandpasses of the filters and the rest–frame bandpasses of the

galaxy, and atmospheric effects during the observations, such as transparency differences between exposures taken through the various filters composing an index. We then proceeded to establish the transformation to the system defined by the Lick standard stars of FFBG85. This multi–step procedure consists of the following. (a) Lick standard stars were observed spectroscopically and their observed energy distributions were put into the standard flux system through the use of flux standards observed nightly (§4.2.1). Our filter bandpasses, shifted to zero velocity, were then integrated numerically on the resulting energy distributions. Notice that the fluxing procedure assured night-to-night stability. In addition, we used Kennicutt's library of galaxy SEDs (Kennicutt 1992) to test the index behavior with empirical composite populations. (b) Spectroscopy of the bright central region of our program galaxies, including two ellipticals, were obtained during the same run and their fluxed energy distributions were integrated numerically within the same filter bandpasses as the standard stars, but shifted to the rest-frame of the galaxy (see §4.2.2). (c) Some additional corrections due to the difference in spectral resolution between the stellar and galactic observations, as well as possible velocity effects, were necessary (see §4.2.2). We next describe each step in detail and give a succinct listing of all steps at the end of §4.2.4. .

4.2.1.   Use of Stellar Observations and Published SEDs

In January, March and June 1995 and in June 1996 we observed spectroscopically 35 stars in common with FFBG85 and covering a wide range in spectral type and metallicity[2].

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[2]Their HR catalogue numbers are as follows: 1346, 1373, 2478, 2600, 2697, 2821, 2854, 3461, 3905, 4365, 4521, 4932, 5227, 5270, 5370, 5480, 5681, 5744, 5826, 5854, 5888, 5901, 5940, 5947, 6014, 6018, 6064, 6103, 6136, 6159, 6299, 6770, 6817, 6872, and 7148.

Figures 2 and 3 show the standard (see FFBG85) versus observed values (filters' definitions) of the indices, which are well represented by straight lines. Linear regressions of the stellar data yield the following relations:

$$\mathrm{Mg2}_{\mathrm{Lick,\ std}} = 1.18(\pm 0.03)\mathrm{Mg2}_{\mathrm{OMM}} + 0.029(\pm 0.006) \quad [\mathrm{mag}] \tag{10}$$

$$\mathrm{Fe5270}_{\mathrm{Lick,\ std}} = 0.67(\pm 0.05)\mathrm{Fe5270}'_{\mathrm{OMM}} + 1.1(\pm 0.2) \quad [\text{Å}] \tag{11}$$

where numbers between parenthesis correspond to a 1σ error on the respective coefficient. In these equations, it is important to emphasize that the $\mathrm{Mg_2}$ and $\mathrm{Fe5270}'$ indices used correspond *both* to the OMM definitions, i.e. they match the OMM filters' bandpasses. The above slopes were essentially identical when derived from the composite populations of a sample of galaxies with published indices which included some of Kennicutt's spectra and two ellipticals and a S0/Sa observed by us, and when derived from stars.

As expected, the slope of the equation for $\mathrm{Mg_2}$ is close to unity, and Figure 2 shows a tight relation, with a dispersion around the mean line of $\sigma \sim 0.03$ `mag`, which includes stars and galaxies. Also as expected, the slope of the equation for Fe5270 differs significantly from unity (Figure 3), and the uncertainty in the slope is larger. The slopes for stars and galaxies are consistent with each other. The Fe5270 plot displays a much larger dispersion than the one for $\mathrm{Mg_2}$, of $\sigma \sim 0.2$ Å. Because the large dispersion around the mean lines for the Fe5270 plots might suggest an effect due to our unorthodox pseudo-index definition, we tested the intrinsec dispersion of the Lick indices by studying the residuals of the values obtained from our high S/N stellar sample when using the standard index definition. Figure 4 shows the histogram of residuals derived by comparing the published indices to the measured values. We obtain an intrinsic dispersion comparable to that of Equation 11 suggesting that the Fe5270 standard system itself is not in general as well determined intrinsically as the $\mathrm{Mg_2}$ one. We conclude that the standard Fe5270 system can be fairly well reproduced from our filter definition ($\mathrm{Fe5270}'$) after correction for the slope indicated

above.

The imaging Mg_2 index and the imaging Fe5270′ pseudo-index were then multiplied by their derived transformation slopes to put the observations of our galaxy (M 100) in the Lick system to within an additive constant which is derived below.

4.2.2. Zero Points

All spectroscopic observations for galaxies were obtained with a slit opened to 6″.1 in order to increase the S/N, and to render accessible a large image section to the zero point adjustement between the spectroscopy and the imagery. This slit width corresponds to a resolution of 34 Å FWHM, far lower than the value used in most studies, and should produce a significant offset with respect to the Lick system.

In order to determine this index offset high-resolution stellar spectra were degraded to match the galaxy spectral resolution and the resulting differences were added to the galaxy indices. In addition the fluxed–Lick correction of 0.017 `mag`, adopted by González et al. (1993) was added to the Mg_2. This combined corrrection was quite consistent with the intercept of the Lick versus Mégantic plot for stars, once the Mégantic stellar observations were placed themselves into the standard Lick IDS dispersion of 8 Å FWHM.

$$Mg_{2\text{Lick, computed}} = Mg_{2\text{OMM}} + 0.018 + 0.017 \quad [\text{mag}] \tag{12}$$

$$Fe5270_{\text{Lick, computed}} = Fe5270_{\text{OMM}} + 1.307 \quad [\text{Å}] \tag{13}$$

where the indices Mg_2 and Fe5270 follow the Lick definitions.

The zero points of the image system were derived by matching the spectroscopic standard indices for the bright central part of the program galaxies to those derived from integration of our filter bandpasses within the exact same region.

4.2.3. Velocity Broadening and Rotational Corrections

Spectral broadening due to velocity dispersion differences across a galaxy can introduce systematic effects in the determination of spectral indices, in particular for Fe5270. Since we are using relatively wide bandpasses in this investigation this effect should not be significant; we have used a spectrum to simulate the effect of a bulge-disk extreme difference of 150 km s^{-1} and found a difference of less than 1% which we disregarded.

As already discussed we have chosen nearly face-on spirals (such as M 100) for our extended program for a number of reasons. Arm-interarm separation is best achieved on these objects because we have more available pixels for a given distance, reddening corrections (see below) are less significant, and differential Doppler effects are clearly smaller. Very large spirals with rotational speeds of order 300 km s^{-1} will shift the effective rest–frame bandpasses of our filters by as much as 5 Å if seen edge-on. In practice this effect, which can be accounted for by using a suitable energy distribution to compute a correction, will be small and in most cases with $i \leq 45\,\mathrm{deg}$ the λ shift will be less than 6% of the bandpass width. For NGC 4321 it is only 1.9 Å and since a spectral simulation shows that the impact on the indices is negligible (well below 1%) we have not computed a correction. Notice also that uncorrected azimuthal integrations will always result in a *broadening* of the bandpass by less than twice the λ shift when averaged over an annulus.

4.2.4. Reddening Corrections

In order to examine the effect of internal absorption on our indices, we have used a representative energy distribution, the nuclear one, and applied different amounts of visual extinction. The results are shown in panels (a) and (b) of Figure 5. Notice the non-monotonic behavior of Mg$_2$, which reaches a maximum correction of $\sim 4\%$ near A_V

= 5 mag. Since we do not expect values of A_V larger than 2–3 mag, we did not apply a reddening correction to our data. We do not expect any significant contribution to an index gradient in the disk of M 100 from a gradient in the dust distribution.

Let us summarize the contents of §4. We: (1) Obtained the instrumental (OMM)–to–standard (Lick) transformations (Equations 10 and 11 of §4.2.1). (2) Measured the indices on the spectra of the bright central regions of the target galaxies using the standard (Lick) filter definitions (§4.2.2). (3) Computed and added the dispersion corrections for both indices, and the flux correction for Mg_2; this placed the values of the indices of the bright central regions in the Lick system (Equations 12 and 13 of §4.2.2). (4) Measured the indices on the images, which were in the OMM system (§4.2.1). (5) Applied the slopes found in (1) in order to transform the OMM filter system into the Lick system. (6) Computed the offsets between the spectroscopic values (from 3) and the imaging values (from 5) (§4.2.2). (7) Obtained the Lick indices at any point along the galaxy profile by multiplying their values on the OMM system by the slopes found in §4.2.1 and adding the offsets found in §4.2.2.

5.   First Results for M 100

We start by showing a sequence of images of M 100, none of which has been deprojected, and all of which have the same orientation and scale. Figure 6 shows this galaxy in V' light, an image obtained by coadding all four narrow band filters. Figure 7 provides an image formed by the $V' - I$ color; this was the reference image for the arm-interarm discrimination described in §4.1.3. Notice in Figure 7 the presence of the well known ring at a radial distance of $10''$ to $22''$ (Arsenault et al. 1988), and the bar extending to about $60''$(Knappen et al. 1996). Figure 8 shows M 100 again in V' light, as in Figure 6, but with the arm pixels and unwanted objects masked. Figures 9 and 10 show the *unmasked* image of M 100 in the Mg_2 and in the $Fe5270'$ index, respectively. In these last two images, which

have been smoothed with a 17×17 pixel square box, stronger indices are coded brighter. Notice that the bar is apparent in Figure 7, but not in figure 9 or 10, suggesting that the bar indices matche those of the disk within the bar radius. There is clear evidence of a Mg_2 gradient, shown in panel (a) of Figure 11 which reaches to about 4 exponential scale lengths. Notice that we do not attempt here or elsewhere in this paper to decompose the bulge/disk contributions. However, examination of the profile decomposition by Kodaira et al. (1986) shows that the bulge dominates the observed surface brightness distribution only within the central 1–2 kpc (and again past 24 kpc). Panel (b) of the same figure shows little evidence, within the errors, of a Fe5270 gradient except perhaps within the inner 5 kpc (the scale is assumed to be 1 kpc $= 12''$, see Table 4). We repeat the above figure in Figure 12, where the horizontal axis is now in units of V surface brightness (the latter from Beckman et al. 1996). Near the center the profiles are probably dominated by the central ring (Arsenault et al. 1988).

There is some indication in Figures 11 and 12 of a change in the Mg_2 gradient near R=5 kpc, which could be due to the effect of the well known bar present in M 100 (see Figure 7). Bars are believed to be efficient carriers of disk material of lower mean abundance from outside the co–rotation radius into the central regions (Friedli & Benz 1995; Courteau et al. 1996; Beauchamp, Hardy & Friedli 1997, in preparation).

Although we refrain from assigning separate Mg and Fe abundances to M 100 within the context of this paper, we use the results of Idiart et al. (1996) (their Equation 4) to transform Figures 11 and 12 into [Mg/Fe] gradients under certain assumptions. Their models are valid for bulge populations, but show a similar evolutionary time dependence for the Mg/Fe and Fe5270 indices, dependence that drops out of the model when the [Mg/Fe] *ratio* is computed. Thus, their computation of this fundamental ratio, for bulges,

is *independent of the mean age of the population*, and is represented by

$$[\mathrm{Mg/Fe}] = -0.042 - 0.2\mathrm{Mg}_2 - 0.063 < \mathrm{Fe} > -7.73(\mathrm{Mg}_2/ < \mathrm{Fe} >) \quad [\mathrm{dex}] \qquad (14)$$

which assumes a minimum time of 1 Gyr for the onset of type Ia supernovae. Here $<\mathrm{Fe}>$ is the mean strength (in Å) of the Fe5270 and the Fe5335 features. Since we have not measured Fe5335, we have collected together the observations of spiral bulges from Idiart et al. (1996) , and Jablonka et al. (1996) to establish a relationship between $<\mathrm{Fe}>$ and Fe5270; the resulting linear correlation, derived from 79 bulges was

$$< \mathrm{Fe} >= 0.91 \, \mathrm{Fe}5270 + 0.091 \quad [\text{Å}] \qquad (15)$$

Introducing this relation into the previous one provides the results shown in Figure 13. There the error bars represent 1σ of the combined errors of the Idiart et al. 1996 relation and those of the $<\mathrm{Fe}>$ versus Fe5270 calibration. If one assumes a radial-independent SNe onset time, then the above computations may represent a reasonable approximation to the disk [Mg/Fe] ratio. This is, however, probably unrealistic, and it is likely that Figure 13 is valid only for the central regions of M 100, where we see a systematic overabundance of α-elements. Observations of a large sample of spirals, as well as more realistic calibrations of the individual Mg and Fe abundances, will be combined in future papers to obtain a more conclusive picture of the distribution of stellar abundances and abundance ratios across spirals.

A. Error Computations For $\mathrm{Mg_2}$ And Fe5270

We assume, for a given function $u = f(x, y, ...)$, where x and y are independant variables, that:

$$\sigma_u^2 = \left(\frac{\partial f(x, y, ...)}{\partial x} \right)^2 \sigma_x^2 + \left(\frac{\partial f(x, y, ...)}{\partial y} \right)^2 \sigma_y^2 + ... \simeq (\Delta u)^2 \qquad (A1)$$

Thus, for $\mathrm{Mg_2}$, the function is

$$\mathrm{Mg_2} = -2.5 \log \left(\frac{\mathcal{F}_{\mathrm{Mg2}}}{\mathcal{F}_{\mathrm{C}}} \right) \qquad (A2)$$

and we have that

$$\sigma_{\mathrm{Mg2}}^2 = 1.086^2 \left(\frac{\sigma_{\mathcal{F}_{\mathrm{Mg2}}}^2}{\mathcal{F}_{\mathrm{Mg2}}^2} + \frac{\sigma_{\mathcal{S}_{\mathrm{Mg2}}}^2}{\mathcal{F}_{\mathrm{Mg2}}^2} + \frac{\sigma_{\mathcal{F}_{\mathrm{C}}}^2}{\mathcal{F}_{\mathrm{C}}^2} + \frac{\sigma_{\mathcal{S}_{\mathrm{C}}}^2}{\mathcal{F}_{\mathrm{C}}^2} \right) \qquad (A3)$$

Where $\mathcal{S}$ denotes the sky level. The standard error of the measurement are given by $\sigma_{\mathrm{mean}} = \sigma / \sqrt{n-1}$:

$$\sigma_{\mathrm{Mg2\,mean}} = 1.086 \sqrt{ \frac{ \left(\frac{\sigma_{\mathcal{F}_{\mathrm{Mg2}}}^2}{\mathcal{F}_{\mathrm{Mg2}}^2} + \frac{\sigma_{\mathcal{S}_{\mathrm{Mg2}}}^2}{\mathcal{F}_{\mathrm{Mg2}}^2} + \frac{\sigma_{\mathcal{F}_{\mathrm{C}}}^2}{\mathcal{F}_{\mathrm{C}}^2} + \frac{\sigma_{\mathcal{S}_{\mathrm{C}}}^2}{\mathcal{F}_{\mathrm{C}}^2} \right) }{ n-1 } } \qquad (A4)$$

The derivation and the assumptions are the same for Fe5270. The corresponding function is

$$\mathrm{Fe5270} = 55 \left[1 - \left(\frac{\mathcal{F}_{\mathrm{Fe5270}}}{\mathcal{F}_{\mathrm{C_w}}} \right) \right] \qquad (A5)$$

We find that

$$\sigma_{\mathrm{Fe5270}}^2 = \left(\frac{55}{\mathcal{F}_{\mathrm{C_w}}} \right)^2 \left(\sigma_{\mathcal{F}_{\mathrm{Fe5270}}}^2 + \sigma_{\mathcal{S}_{\mathrm{Fe5270}}}^2 + \frac{\sigma_{\mathcal{F}_{\mathrm{C_w}}}^2 + \sigma_{\mathcal{S}_{\mathrm{C_w}}}^2}{\mathcal{F}_{\mathrm{C_w}}} \right) \qquad (A6)$$

which gives

$$\sigma_{\mathrm{Fe5270\,mean}} = \frac{ \left(\frac{55}{\mathcal{F}_{\mathrm{C_w}}} \right) \sqrt{ \sigma_{\mathcal{F}_{\mathrm{Fe5270}}}^2 + \frac{\sigma_{\mathcal{F}_{\mathrm{C_w}}}^2 + \sigma_{\mathcal{S}_{\mathrm{C_w}}}^2}{\mathcal{F}_{\mathrm{C_w}}^2} } }{ \sqrt{n-1} } \qquad (A7)$$

REFERENCES

Arimoto, N., Jablonka, P., 1991, AA, 249, 374

Arsenault, R., Boulesteix, J., Georgelin, Y., Roy, J.-R., 1988, A&A, 200, 29

Baum, W.A., Thomsen, B., Morgan, B.L., 1986, ApJ, 301, 83

Beckman, J.E., Peletier, R.F., Knapen, J.H, Corradi, R.L.M. & Gentet, L.J., 1996 ApJ, 467, 175

Belley, J., Roy, J.-R., 1992, ApJS, 78, 61

Brewer, J. P., Richer, H. B., & Crabtree, D. R., 1995, AJ, 109, 2480

Burstein, D., Faber, S.M., Gaskell, and Krumm, N. 1984, ApJ, 287, 586

Casuso, E., Vazadekis, A., Peletier, R.F., Beckman, J.E., 1996, ApJ, 458, 533

Chavez, M., Malagnini, M.L., Morossi, C., 1995, ApJ, 440, 210

Chavez, M., Malagnini, M.L., Morossi, C., 1996, ApJ, 471, 726

Courteau, S., De Jong, R., & Broeils, A. H., 1996, ApJ, 457, L73

Couture, J., Hardy, E.J., 1988, AJ, 96, 867

Carollo, C.M., Danziger, I.J., Buson L., 1993, MNRAS, 265, 553

Davies, Roger L., Sadler, Elaine M., Peletier, Reynier F., 1993, MNRAS, 262, 650

Davidge, T.J., 1992, AJ, 103, 1512

Davidge, T.J., 1997, AJ(preprint)

Faber, S.M., Friel, E.D., Burstein, D. & Gaskell, C.M., 1985, ApJS, 57, 711 (=FFBG85)

Friedli, D., Benz, W., 1995, A&A, 301, 649

González, J.J., Faber, S.M. Worthey, G., 1993, BAAS, 183, 4205

Gorgas J., Estathiou, G., Salamanca-Aragon, A., 1990, MNRAS, 245, 217

Idiart, T.P., De Freitas Pacheco, J.A., Da Costa, R.D., 1996, AJ, 112, 2541

Jablonka, P., Martin, P., Arimoto, N., 1996, AJ, 112, 1415

Kennicutt, R.C. jr, 1992, ApJS, 79, 255

Kodaira, K., Watanabe, M., & Okamura, S. , 1986, APJS, 62, 703

Knapen, J.H., Beckman, J.E., 1996, MNRAS, 283, 251

Martin, P., Roy, J.-R., 1994, ApJ, 424, 599

Monteverde, M.I., Herrero, A., Lennon, D.J., Kudritzki, R.-P., 1997, ApJ Lett, 474, L107

Scowen, P.A., Dufour, R.J., Hester, J.J., 1992, AJ, 104, 92

Thomsen, A., Baum, W.A., 1989, ApJ, 347, 214

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H.G., Bata, R.J., Paturel, G. & Fouqué,
        P., 1991, Third Reference Catalogue of Bright Galaxies, (Springer, New York)

Wadsworth, H.M., 1990, Handbook of Statistical Methods for Engineers and Scientists,
        (McGraw-Hill, New York)

Warmels, R.H., 1986, Ph.D. thesis, Rijksuniversiteit te Groningen, Groningen

Worthey, G., 1994, ApJS, 95, 107

Worthey, G., Faber, S.M. & González, J., 1992, ApJ, 398, 69

Zaritsky, Dennis, Kennicutt, Robert C. Jr, Huchra, John P., 1994, ApJ, 420, 87

Fig. 1.— Top panel: K star SED redshifted to 2000 km s^{-1} to match the filter set shown below. The Mg and Fe features measured in this investigation are identified. Bottom panel: The transmission curves of our filter set at 23 °C. The BC and RC labels identify the blue and red continua respectively. The solid horizontal lines represent the three Lick bandpasses that define the standard Mg$_2$ index; the discontinuos horizontal lines those of the standard Fe5270 index.

Fig. 2.— Transformation between standard (Lick) and measured Mg$_2$ index (OMM filter definition) derived from integration of the stellar spectra (open circles), of Kennicutt's galaxies (asteriscs), and of the three galaxies of our program (NGC 2655, 2974 and 4473; solid boxed) which have published standard Mg$_2$ indices . The least square parameters of the fit are indicated, with their errors within parenthesis.

Fig. 3.— Same as Figure 2, but for the stellar Fe5270 data.

Fig. 4.— Histogram of differences between published Lick Fe5270 values (from FFBG85) and measured Fe5270 values.

Fig. 5.— The dependence of index values on internal absorption as simulated using the measured central spectrum of M 100.

Fig. 6.— Direct image of the central 13′ of M 100 in V' band. The reference horizontal line is 1′ long, and the circle has a radius corresponding to 1 isophotal radius (R25 = 222″). North is up, east to the left. All five images of M100 (see below) have the same scale and field of view, and are unprojected

Fig. 7.— M100 in $V' - I$ color.

Fig. 8.— Same as Figure 6 but with arms and bright stars masked.

Fig. 9.— The Mg$_2$ index unmasked "image" of M 100. The original image has been median

filtered with a 17×17 pixel square box.

Fig. 10.— Same as Figure 9 but for the Fe5270$'$ index.

Fig. 11.— Index profiles as function of deprojected radial distance in arcsecs and in kpc.

Fig. 12.— Index profiles as function of V surface brightness.

Fig. 13.— Model abundance ratio [Mg/Fe] as function of radial distance and V surface brightness.

Figure a) shows Relative Flux versus wavelength with labels Fe5270 and Mg$_2$.

Figure b) shows Transmittance [%] versus λ [Å] with labels Mg$_{2Lick}$, Fe5270$_{Lick}$, BC, Mg$_2$, Fe5270, RC.

slope = 1.18(0.03)
intercept = 0.029(0.006)